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5       **METHOD AND APPARATUS FOR PRODUCTION OF  $^{213}\text{Bi}$  FROM A HIGH  
ACTIVITY  $^{225}\text{Ac}$  SOURCE**

Cross-Reference To Related Applications

This application claims priority to Provisional Application Ser. No. 60/457,544  
10 filed 03/24/03, the entire contents of which are incorporated herein by this reference.

Statement Regarding Federally Sponsored Research Or Development

This invention was made with Government support under Contract  
DE-AC0676RLO1830 awarded by the U.S. Department of Energy. The Government has  
certain rights in the invention.

15       Background Of The Invention

The use of radiation to kill or neutralize unwanted cell growth such as cancer has  
led to increasing interest in various species of radioactive isotopes. Of particular interest  
are radioactive isotopes, such as  $^{213}\text{Bi}$ , which emit alpha radiation, or alpha emitters,  
because the alpha radiation emitted by these radioactive isotopes does not penetrate  
20 deeply into tissue.  $^{213}\text{Bi}$  is normally produced as a daughter product of  $^{229}\text{Th}$  (half-life  
 $=7,300\text{ yr}$ ). The radioactive decay chain in which  $^{213}\text{Bi}$  is found is well known:  $^{233}\text{U}$  (half-  
life = $1.62 \times 10^5\text{ yr}$ )  $\rightarrow$   $^{229}\text{Th}$  (half-life = $7,300\text{ yr}$ )  $\rightarrow$   $^{225}\text{Ra}$  (half-life = $14.8\text{ day}$ )  $\rightarrow$   $^{225}\text{Ac}$   
(half-life = $10\text{ day}$ )  $\rightarrow$   $^{213}\text{Bi}$  (half-life = $46\text{ min}$ ).

One Bi generator system used to separate and isolate  $^{213}\text{Bi}$  from  $^{225}\text{Ac}$  is described  
25 in US Patent 5,749,042 to Bray, et al. (The entire contents of the Bray patent, together  
with any and all other patents, papers, articles, or other written materials referenced in  
this application are hereby fully incorporated into the disclosure of this application as if  
they had been reproduced herein in their entirety.) In the Bray patent, a solution  
containing the radioactive isotope  $^{225}\text{Ac}$  and hydrochloric acid is combined with an anion

exchange resin, whereupon the daughter product of the  $^{225}\text{Ac}$ ,  $^{213}\text{Bi}$ , is absorbed from the "cow" solution and adheres onto the anion exchange resin as a chloride complex. Traces of the  $^{225}\text{Ac}$  cow and the acid from the anion exchange resin are then removed, leaving a chloride complex which adheres the  $^{213}\text{Bi}$  to the anion exchange resin. A 5 stripping solution is then provided which weakens or destroys the chloride complex, thereby releasing the  $^{213}\text{Bi}$  from the anion exchange resin. The "cow" solution containing is recovered and used for subsequent continuing production of the  $^{213}\text{Bi}$  after its ingrowth.

Because of its short half-life of 45.6 minutes, it is highly advantageous to generate 10  $^{213}\text{Bi}$  at the point of use, typically in a clinical setting. While  $^{213}\text{Bi}$  can be conveniently obtained from an  $^{225}\text{Ac}$  generator system such as the system taught by Bray et al., there are significant problems associated with the use of these known generator systems in clinical settings. For example, a generator system that generates significant volumes of solvents can create significant expense, as these solvents typically require expensive and 15 specialized methods for disposal. The generator system must also be capable of reliably operating with high levels of  $^{225}\text{Ac}$  (e.g., 100-150 mCi) over a period of several weeks.

Another approach for generating the radioactive isotope  $^{213}\text{Bi}$  is presently in use at the Memorial Sloan Kettering Cancer Center, and is described in Applied Radiation and Isotopes, 50 (1999) 895-904, "An  $^{225}\text{Ac}/^{213}\text{Bi}$  generator system for therapeutic clinical 20 applications: construction and operation", McDevitt et al. and Applied Radiation and Isotopes, "Breakthrough of  $^{225}\text{Ac}$  and its Radionuclide Daughters, 55 (2001) 667-678, Ma et al. According to this method, an Ac-225 source is distributed on a small column of the polymer-based cation exchange resin (e.g., AG MP-50, Dowex-50, etc.), which has good affinity and selectivity for  $^{225}\text{Ac}$  over  $^{213}\text{Bi}$  in HCl media. The  $^{213}\text{Bi}$  product is 25 periodically eluted using a suitable eluent solution, such as, a 0.1 M HCl/0.1 M NaI solution, while  $^{225}\text{Ac}$  remains on the column during the useful life of the generator system. While this system does have certain advantages, the cumulative radiation dose to a small mass of a functionalized organic resin by a  $^{225}\text{Ac}$  source, typically having activity greater than 20 mCi, is substantial. This intense radiation dose will typically cause 30 damage to the sorbent material and result in generator failure over extended periods of operation. Furthermore, the continuous generation of radical species on the resin and in

the generator eluate can lead to poor radiochemical labeling yields, and a poor recovery of the radioactive isotope product. Therefore, the use of the polymer-based sorbent materials in a single generator column of a small volume present numerous drawbacks for use as generator systems in clinical environments.

5 An automated generator system using a  $^{225}\text{Ac}$  source has also been reported previously which sought to alleviate concerns regarding the radiolytic degradation of the resin (Egorov et al., 1998, U.S. Patent No. 6,153,154). Compared to the column generator format, this liquid source approach is more difficult to implement in an automated sterile regime, and requires the use of disposable fluidic components.

10 Wu et al. (*Radiochimica Acta*, 79, 141-144, 1997) described a tandem-column generator system using a silica-gel based extraction chromatographic material for  $^{225}\text{Ac}$  storage. A secondary cation exchange column was used to capture the  $^{213}\text{Bi}$  eluted from the primary column in 1 M solution of hydrochloric acid. A substantial dilution of the eluent (about ten-fold) was necessary prior to loading  $^{213}\text{Bi}$  on the cation exchange column, which makes operation of such a generator system cumbersome and which also leads to generation of significant quantities of waste. However, the use of a silica-gel based material was noted to improve radiolytic stability of the generator system.  
15 Moreover, the tandem column approach improved the  $^{213}\text{Bi}$  product purity and provided additional safety with regard to the  $^{225}\text{Ac}$  breakthrough.

20 Thus, despite these and other advances, there remains a need for a  $^{213}\text{Bi}$  generator system that can be used in a clinical setting, and which minimizes the creation of secondary wastes and which provides the  $^{213}\text{Bi}$  in a form which is compatible with biological applications.

#### Brief Summary Of The Invention

25 Accordingly, it is an object of the present invention to provide a method and apparatus for isolating and purifying a  $^{213}\text{Bi}$  radioactive isotope from an  $^{225}\text{Ac}$  source without generating excessive waste.

It is a further object of the present invention to provide an automated apparatus for isolating and purifying a  $^{213}\text{Bi}$  radioactive isotope from an  $^{225}\text{Ac}$  source.

It is a further object of the present invention to provide an automated apparatus for isolating and purifying a  $^{213}\text{Bi}$  radioactive isotope from an  $^{225}\text{Ac}$  source which avoids the need for additional solutions or other modifications necessary to effect dilution, pH adjustment, or other chemical and/or physical modifications of the solvent used to 5 separate the  $^{213}\text{Bi}$   $^{225}\text{Ac}$  source.

These and other objects are accomplished by providing a primary column having an inlet, an outlet, and a primary sorbent which preferentially retains  $^{225}\text{Ac}$  over  $^{213}\text{Bi}$  when exposed to a compatible solvent. A secondary column having an inlet and an outlet is also provided, wherein the inlet is in communication with the outlet of the primary 10 column. The secondary column also has a secondary sorbent which retains  $^{213}\text{Bi}$  when exposed to a mixture of the compatible solvent and  $^{213}\text{Bi}$ .  $^{225}\text{Ac}$  is first loaded onto the primary sorbent. The compatible solvent is then flowed through the primary column and into the secondary column, thereby transferring  $^{213}\text{Bi}$  formed as a radioactive decay product of the  $^{225}\text{Ac}$  in the primary column to the secondary column. The  $^{213}\text{Bi}$  is 15 retained on the secondary sorbent, by flowing an eluent through the secondary column, the  $^{213}\text{Bi}$  may be removed from the secondary column, and then used, for example in a radiotherapeutic application. One aspect of the present invention which provides significant advantages when compared to prior art systems for generating  $^{213}\text{Bi}$  radioactive isotopes from an  $^{225}\text{Ac}$  radioactive isotope source is a result of the present 20 invention's the use of a "compatible solvent." When combined with an appropriate primary sorbent and an appropriate secondary sorbent, a "compatible solvent" will simultaneously preferentially remove  $^{213}\text{Bi}$  radioactive isotopes from the first sorbent, while allowing  $^{213}\text{Bi}$  radioactive isotopes to be retained on the secondary sorbent, without having to dilute or otherwise chemically or physically modify or alter the solvent. In this 25 manner, a highly purified  $^{213}\text{Bi}$  radioactive isotope can be retained on the secondary sorbent without requiring an intermediate step, such as, for example, dilution or altering the pH of the solvent, in between the step of removing the  $^{213}\text{Bi}$  radioactive isotope from the primary sorbent and the step of retaining the  $^{213}\text{Bi}$  radioactive isotope on the secondary sorbent. This allows the isolation and purification of the  $^{213}\text{Bi}$  radioactive 30 isotope without generating excessive waste, and/or configuring the system to provide additional solutions or other modifications necessary to effect dilution, pH adjustment, or

other chemical and/or physical modifications of the solvent. In this manner, the method of the present invention greatly minimizes the requirements for additional fluids, and the valves, pumps, and reservoirs associated with such additional fluids, used to accomplish the separation. This in turn simplifies construction of the apparatus of the present

5 invention, particularly in an automated configuration, where the apparatus of the present invention is configured to isolate and purify  $^{213}\text{Bi}$  radioactive isotopes automatically. Further, since the compatible solvent is not diluted and the  $^{213}\text{Bi}$  is concentrated on the secondary column, a larger mass of the primary sorbent may be used in combination with the same amount of solvent ultimately flowed through the second sorbent, when

10 compared to prior art systems. In this manner, the same amount of  $^{225}\text{Ac}$  is distributed over a larger mass of the primary sorbent, reducing damage to the sorbent material caused by the radioactive attack of the  $^{225}\text{Ac}$ , reducing the frequency of generator failure, and allowing longer periods of operation without interruption. This advantage of the present invention is of particular importance when the present invention is used to

15 generate  $^{213}\text{Bi}$  radioactive isotopes in a clinical environment for cancer treatments. In such a circumstance, failures of a  $^{213}\text{Bi}$  generator could cause delays in carefully scheduled radiotherapy treatments, thereby interfering, for example, with an optimal treatment regimen for life threatening cancerous growths.

As used herein, a “compatible solvent” is defined as a solvent which will

20 preferentially remove  $^{213}\text{Bi}$  radioactive isotopes from a primary sorbent without removing  $^{225}\text{Ac}$  radioactive isotopes, and then allow  $^{213}\text{Bi}$  radioactive isotopes removed from the primary sorbent to be retained on a secondary sorbent, without having to dilute or otherwise chemically or physically modify the compatible solvent in between exposure to the primary and secondary sorbents. Those having the benefit of this disclosure and

25 ordinary skill in the art will therefore recognize that a given solvent which would be considered “compatible” when used with one set of primary and secondary sorbents, may not be considered “compatible” when used with another set of primary and secondary sorbents. Thus, the determination of whether or not a particular solvent is “compatible” can only be determined in the context of a particular set of primary and secondary

30 sorbents, in much the same manner, for example, that a particular solution can only be considered as “basic” or “acidic” when it is compared to another solution.

Preferred primary sorbents include inorganic matrices impregnated with sulfonic, phosphoric, or phosphonic acid extractants, and combinations thereof, polymeric matrices impregnated with sulfonic, phosphoric, or phosphonic acid extractants, and combinations thereof, and said functionalities grafted onto supports, including polymeric supports,  
5 silica supports, inorganic particulate supports, and combinations thereof. The resin may be chelating resins, cation exchange resins, and combinations thereof. Chelating resins include materials having a diphosphonic acid, organophosphoric acid or other chelating functionality grafted on the support. Cation exchange resins include materials having a sulfonic acid functionality grafted on the support and materials having carboxylic acid  
10 functionalities grafted on the support.

The preferred secondary sorbent is an anion exchange resin grafted on either polymeric supports, silica supports, inorganic supports, and combinations thereof. The preferred anion exchange resin is a long chain ammonium salt, and more preferably a quaternary ammonium salt, a tertiary ammonium salt, or a combination thereof. The  
15 secondary sorbent can be utilized in the column form in the form of a disc or membrane.

Compatible solvents include HCl solutions. In one configuration, an HCl solution of about 1 M is preferred. In another configuration, an HCl solution of between about 0.1 and 0.2M is preferred.

In one configuration, an eluent of sodium acetate solution between about 0.1 and  
20 0.5 M with a pH of about 5 or acetic acid concentration of 0.5 M is preferred.

Apparatus that are considered as falling within the scope of the present invention can be configured many ways, however, all such apparatus have certain common elements. As shown in Fig. 1, the apparatus of the present invention has a compatible solvent 1, a primary column 2 having an inlet 3, an outlet 4, a primary sorbent 5 which  
25 preferentially retains  $^{225}\text{Ac}$  over  $^{213}\text{Bi}$  when exposed to the compatible solvent 1, a secondary column 6 having an inlet 7 and an outlet 6. The inlet 7 of the secondary column in communication with the outlet 4 of the primary column, and the secondary column 6 further has a secondary sorbent 9 which retains  $^{213}\text{Bi}$  when exposed to a mixture of the compatible solvent and  $^{213}\text{Bi}$ .

As further illustrated in Fig. 1, preferred configurations of the apparatus of the present invention may further include an eluent reservoir **10** containing a eluent **11**, the eluent **11** capable of removing  $^{213}\text{Bi}$  from the secondary sorbent **9**, and the eluent reservoir **10** in communication with the secondary column **2**. Preferred configurations 5 may further include at least one pump **12** in communication with the primary column **2** and configured to pump the compatible solvent **1** through the primary column **2** and the secondary column **6**. Preferred configurations of the apparatus of the present invention may further include a compatible solvent reservoir **13**, a first valve **14**, and a controller **15**. The first valve **14** is advantageously disposed to control the flow of the compatible 10 solvent **1** to the primary column **2**. The controller **15** is in communication with the pump **12** and the first valve **14** and is thereby configured to operate the pump **12** and the first valve **14** such that the first valve **14** is opened and the compatible solvent **1** is pumped through the primary column **2** and the secondary column **6** at predetermined intervals to retain said  $^{213}\text{Bi}$  on the secondary sorbent **9**. A second valve **17** may further be provided 15 and disposed to control the flow of the eluent **11** through the secondary column **6**. A second outlet **16** on the secondary column **6**, or an equivalent arrangement, is also preferred, so long as the arrangement allows the eluent **11** to be flowed through the secondary column **6** in the opposite direction the compatible solvent **1** is flowed through the secondary column **6**.

20 While those skilled in the art having the benefit of this disclosure will readily recognize that multiple pumps may be provided, a solution that allows the use of a single pump **12** may utilize a third valve **18** which is configured to allow the pump to alternate between flowing the compatible solvent **1** through the primary column **2** and the secondary column **6**, and flowing the eluent **11** through the secondary column **6**. As 25 shown in Fig. 1, the controller **15** may further be configured to control the first valve **14**, the second valve **17**, the third valve **18**, and the pump **12**, so that, alternately the compatible solvent **1** is first pumped through the primary column **1** and the secondary column **6** at predetermined intervals to retain said  $^{213}\text{Bi}$  on the secondary sorbent **9**, and the eluent **11** is then pumped through the secondary column **6**, providing the  $^{213}\text{Bi}$  at the 30 second outlet **16** of the secondary column **6**.

While the illustration shown in Fig. 1 shows one workable design of the apparatus of the present invention, those having skill in the art and the benefit of this disclosure will readily recognize that numerous alternative arrangements are possible. Additional pumps and valves, for example, may be deployed. These additional pumps and valves can be

5 positioned, for example and not to be limiting, to prevent flow between the primary column **2** and the secondary column **6** when the eluent **11** is removing the <sup>213</sup>Bi from the secondary sorbent. Additionally, a wide variety of alternate piping arrangements, together with additional outlets and inlets to the primary and secondary columns might be provided, for example, and not meant to be limiting, to allow the introduction of a wash

10 solution. These arrangements should be considered as being encompassed by the present invention, provided that they utilize a primary and a secondary column in combination with a compatible solvent.

Further, the controller may be a microcontroller which may be limited to the operation of the apparatus of the present invention, or it might be operated on a general purpose computer, for example running a software program that has been designed to control the valves and pumps with the correct timing, and which is operated to perform more functions beyond the control of the apparatus. In either case, means for a user to monitor the operation of the controller, such as a CRT display, and/or means, such as a mouse or a keyboard, that allow a user to change the parameters of the controller, such as

15 the timing or quantities of compatible solvent that are flowed through the primary and secondary columns, are intended to be included in the meaning of the term "controller" as used by the applicant. These various configurations, together with valves, syringes, and pumps which may be operated by electronic signals, by using solenoids for example, are common in automated control systems and are well understood by those having ordinary

20 skill in the art. No further description is therefore required to enable those having ordinary skill in the art to devise suitable automated control systems that will successfully control and operate the apparatus described herein.

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In addition to various alternative arrangements for additional valves and pipes, additional primary columns **2**, similar or identical to the primary column **2** shown in Fig.

1 may be employed to increase the production rate of the  $^{213}\text{Bi}$ . These additional primary columns may be employed in series or in parallel, as determined by the user.

#### Brief Description Of The Several Views Of The Drawing

FIG. 1 is a schematic drawing of one possible arrangement of the present invention

- 5 showing the key features of the present invention together with numerous optional features.

FIG. 2 is a graph showing the uptake characteristics of a silica grafted sorbent material having a crown ether chelating functionality for both  $^{213}\text{Bi}$  and  $^{225}\text{Ac}$  as a function of the molar concentration of an HCl solvent.

10 FIG. 3 is a graph showing the uptake characteristics of a silica grafted cation exchange sorbent for both  $^{213}\text{Bi}$  and  $^{225}\text{Ac}$  as a function of the molar concentration of a NaCl solvent in a mixture with 0.01 M HCl, where the molar concentration of the HCl is held constant.

15 FIG. 4 is a graph showing the uptake characteristics of a silica sorbent impregnated with diphosphonic extractant (Actinide Resin) for both  $^{213}\text{Bi}$  and  $^{225}\text{Ac}$  as a function of the molar concentration of an HCl solvent.

FIG. 5 is a set of graphs showing the uptake characteristics of a polymer grafted cation exchange material; a silica impregnated with diphosphonic extractant (Actinide Resin); and a polymer grafted strongly basic anion exchanger for both  $^{213}\text{Bi}$  and  $^{225}\text{Ac}$  as a function of the molar concentration of an HCl solvent.

#### Detailed Description Of The Invention

A variety of experiments were undertaken to demonstrate various combinations of materials suitable for use as the compatible solvent and for use as primary and secondary 25 sorbents. In addition to finding a secondary sorbent suitable for use with a compatible solvent, the ability of the secondary sorbent to elute  $^{213}\text{Bi}$  with an elutant that would be acceptable for use as a solution in which the  $^{213}\text{Bi}$  could be successfully combined with

therapeutic biomolecules was also a consideration. While these experiments show various combinations that achieve the objectives of the present invention, they should in no way be viewed as limiting the scope of the present invention. As described in the forgoing Summary of the Invention, a wide variety of materials are capable of being 5 effectively utilized in the present invention. Accordingly, the experiments described below should only be considered as illustrative examples of the present invention, and the scope of the claims that follow should in no way be viewed as limited by or to these illustrative examples.

One material investigated for use as a sorbent is a silica grafted sorbent material 10 having a crown ether chelating functionality sold under the trade name "Superlig 643" by IBC Advanced Technologies of American Fork, UT. Figure 2 shows the uptake characteristics of this sorbent for both  $^{213}\text{Bi}$  and  $^{225}\text{Ac}$ . As shown in the graph, the selection of the compatible solvent of about 1 M HCl, this material preferentially retains  $^{225}\text{Ac}$ , while  $^{213}\text{Bi}$  is not retained and is elutable. This material is thus suitable for the 15 elution of the primary column. As shown in Figure 2, the molar strength of the HCl used as a compatible solvent with this sorbent need not be exactly 1 M. Accordingly, those having skill in the art having the benefit of this disclosure will appreciate that the use of the term "about" in describing the molar concentration of the compatible solvent is intended to recognize that a range of molar concentration will meet the objectives of the 20 present invention, and that any and all of those concentrations that meet the definition of "compatible solvent" as set forth in this disclosure should be included.

Figure 3 shows the uptake characteristics of a silica grafted cation exchange sorbent sold under the tradename SCX by SUPELCO of Bellefonte, PA showing selection of the compatible solvent of between about 0.2 M NaCl and about 0.01 M HCl 25 for the elution of the primary column. As shown in the graph, when exposed to a compatible solvent of about 0.2 M NaCl mixed with 0.01 M HCl, this material preferentially retains  $^{225}\text{Ac}$ , while  $^{213}\text{Bi}$  is not retained and is elutable.

Figure 4 shows the uptake characteristics of a silica sorbent impregnated with diphosphonic extractant (Actinide Resin) available from Eichrom Technologies, Inc, of

Darien, IL. As shown in Figure 4, a compatible solvent of 2 M HCl is appropriate for the elution of the primary column.

Figure 5 shows the  $^{213}\text{Bi}$  uptake characteristics of a polymer grafted cation exchange material sold under the tradename MP-50 by Bio-Rad Laboratories, Hercules, CA; a silica impregnated with diphosphonic extractant (Actinide Resin) available from Eichrom Technologies, Inc, of Darien, IL.; and a polymer grafted strongly basic anion exchanger sold under the tradename MP-1M by Bio-Rad Laboratories, Hercules, CA. Figure 5 thus shows how the selection of the compatible solvent for the operation of the two tandem column generator systems is possible. The  $^{213}\text{Bi}$  is readily eluted from cation exchange material using about 0.6-1 M HCl, and the  $^{213}\text{Bi}$  is readily eluted from Actinide Resin using 2 M HCl. In both cases, the  $^{225}\text{Ac}$  will be effectively retained by the anion exchange material. Thus, for the systems where the anion exchange material is used in the primary column and the cation exchange material is used in the secondary column, 0.6-1 M HCl solution represents a compatible solvent, and for systems where the anion exchange material is used in the primary column and where the Actinide Resin is used as the secondary column, 2 M HCl represents a compatible solvent.

Additional experiments were conducted to demonstrate the tandem column generator operation in the flow regime. In the specific example the primary column was comprised of strongly acidic cation exchanger (MP-50) column (bed volume 3 mL) with 3 mCi of  $^{225}\text{Ac}$  uniformly distributed throughout the two thirds of the column bed. The secondary column was comprised of the strongly basic anion exchanger resin (MP-1M) with the bed volume of 0.120 mL. The primary column was eluted using 6 mL of the 1 M HCl at the flow rate of 3 mL/min. The eluent was delivered to the secondary column connected to the outlet of the primary column. Next the secondary column was rinsed with 1 mL of 1 mM HCl and then eluted using 6 mL of 0.5 acetic acid at flow rate 2 mL/min. The eluent was collected and used for subsequent labeling of the CHX-A-HuM-195 monoclonal antibody used in the treatment of leukemia. The tandem column total generator yield was 92%. The IgG labeling yield determined by the ITLC was 91%.

## CLOSURE

While a preferred embodiment of the present invention has been shown and described, it will be apparent to those skilled in the art that many changes and modifications may be made without departing from the invention in its broader aspects.

- 5 The appended claims are therefore intended to cover all such changes and modifications as fall within the true spirit and scope of the invention.